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(54) **METHOD AND APPARATUS FOR PERFORMING TARGETED POLISHING VIA MANIPULATION OF MAGNETIC-ABRASIVE FLUID**

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(52) **U.S. Cl.**
CPC ***B24B 31/112*** (2013.01); ***B24B 1/005*** (2013.01)

(58) **Field of Classification Search**
CPC B24B 31/102; B24B 31/112; B24B 1/005
USPC 451/36, 113, 35
See application file for complete search history.

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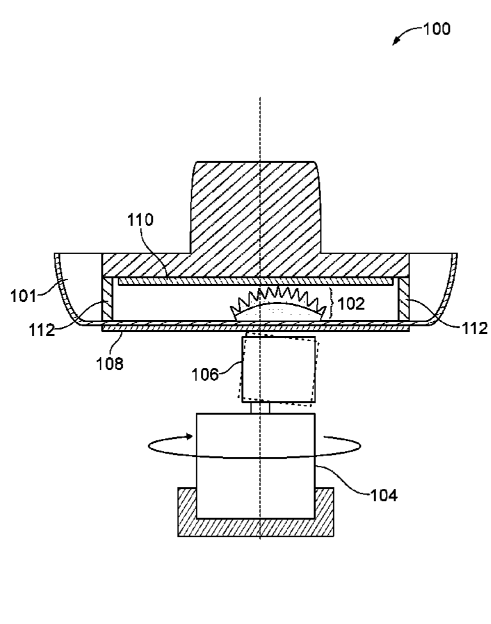
(57) **ABSTRACT**

A magnetic field manipulated localized polishing system includes a container holding a volume of a magnetic abrasive fluid. The magnetic abrasive fluid contains abrasive particles. A motor is positioned under the container. A magnet is coupled to the motor such that the motor induces rotation of the magnet. A workpiece is suspended in the container.

18 Claims, 5 Drawing Sheets



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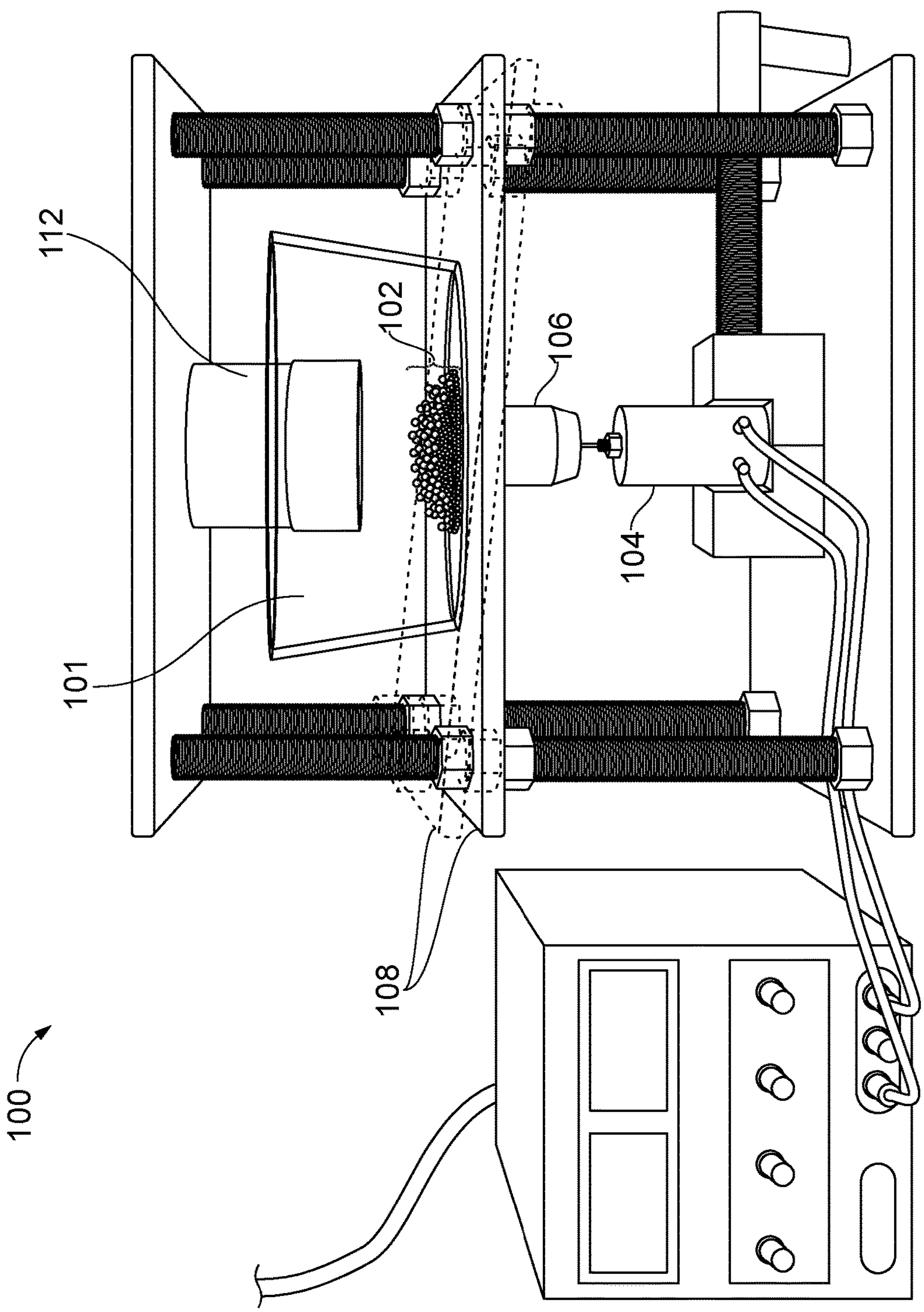

FIG. 1A

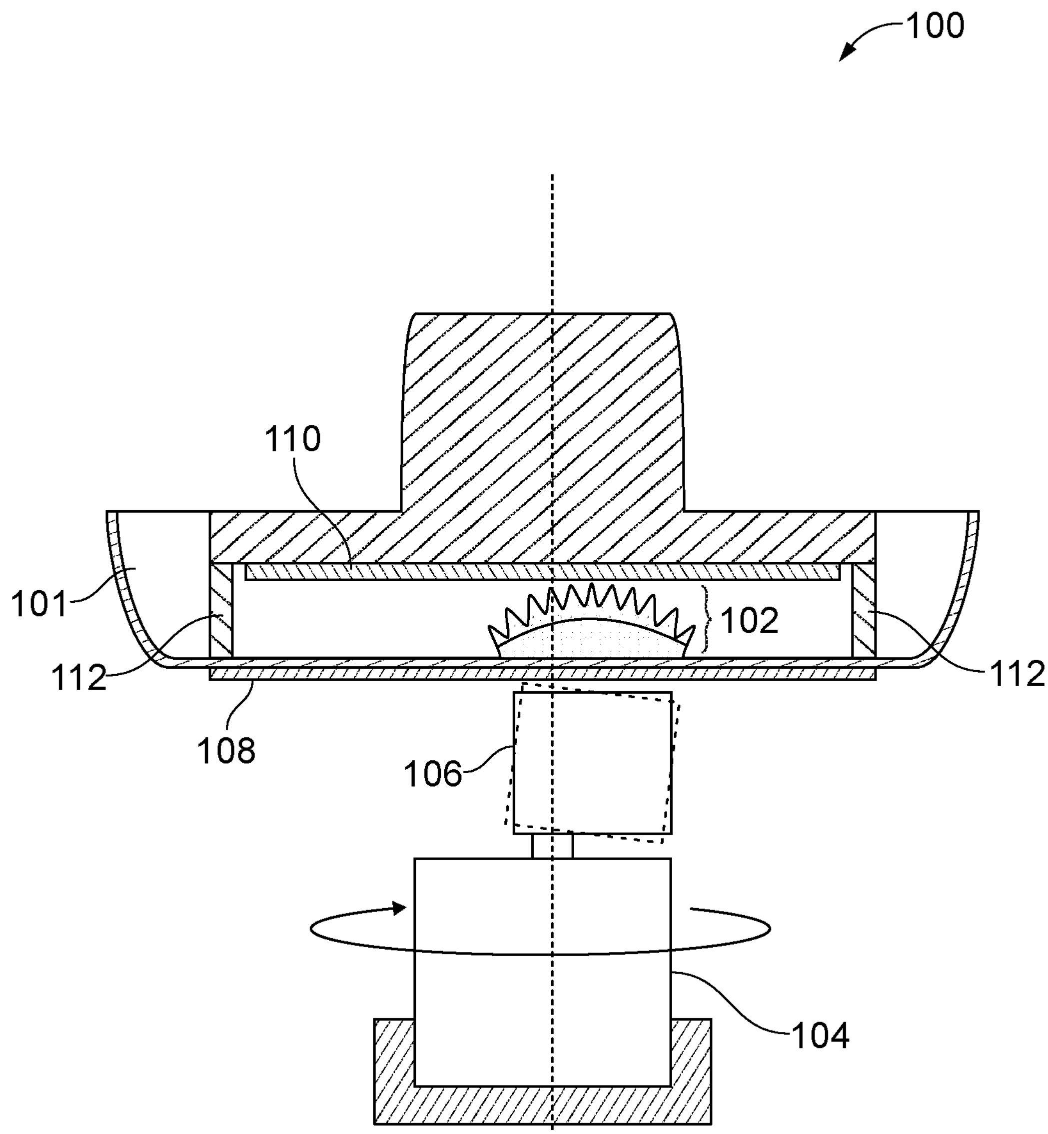

FIG. 1B

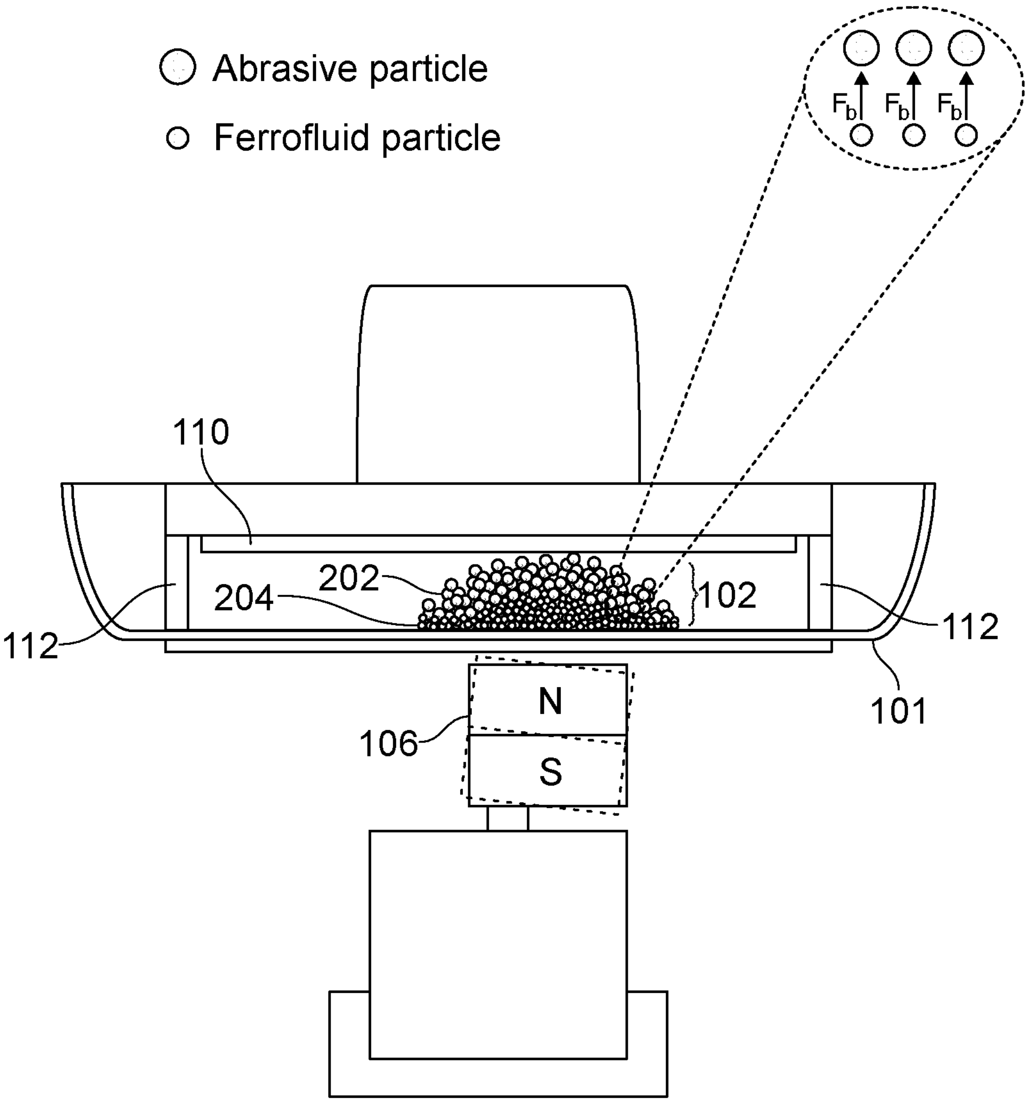
Abrasive particle
Ferrofluid particle
Fb
Fb
Fb
110
202
204
102
112
112
101
N
S
106

FIG. 2A

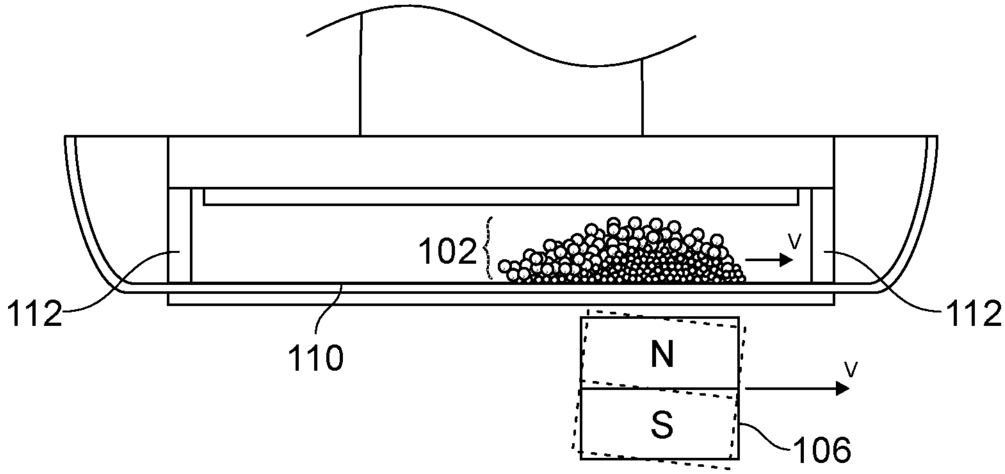

FIG. 2B

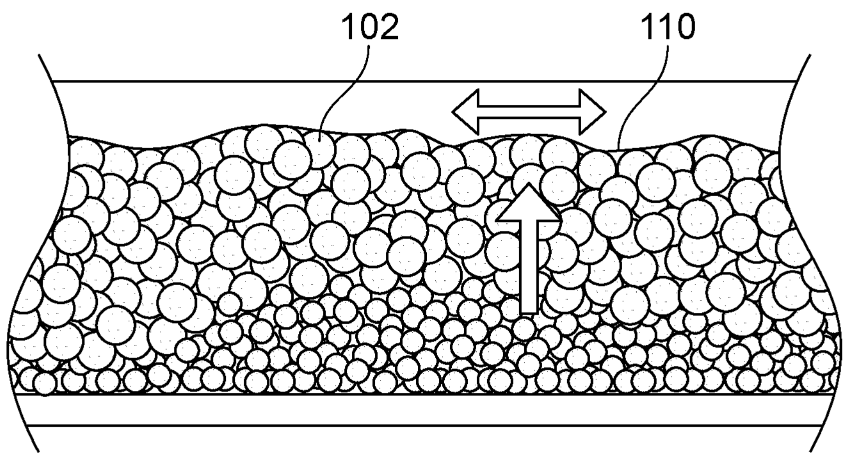

FIG. 2C

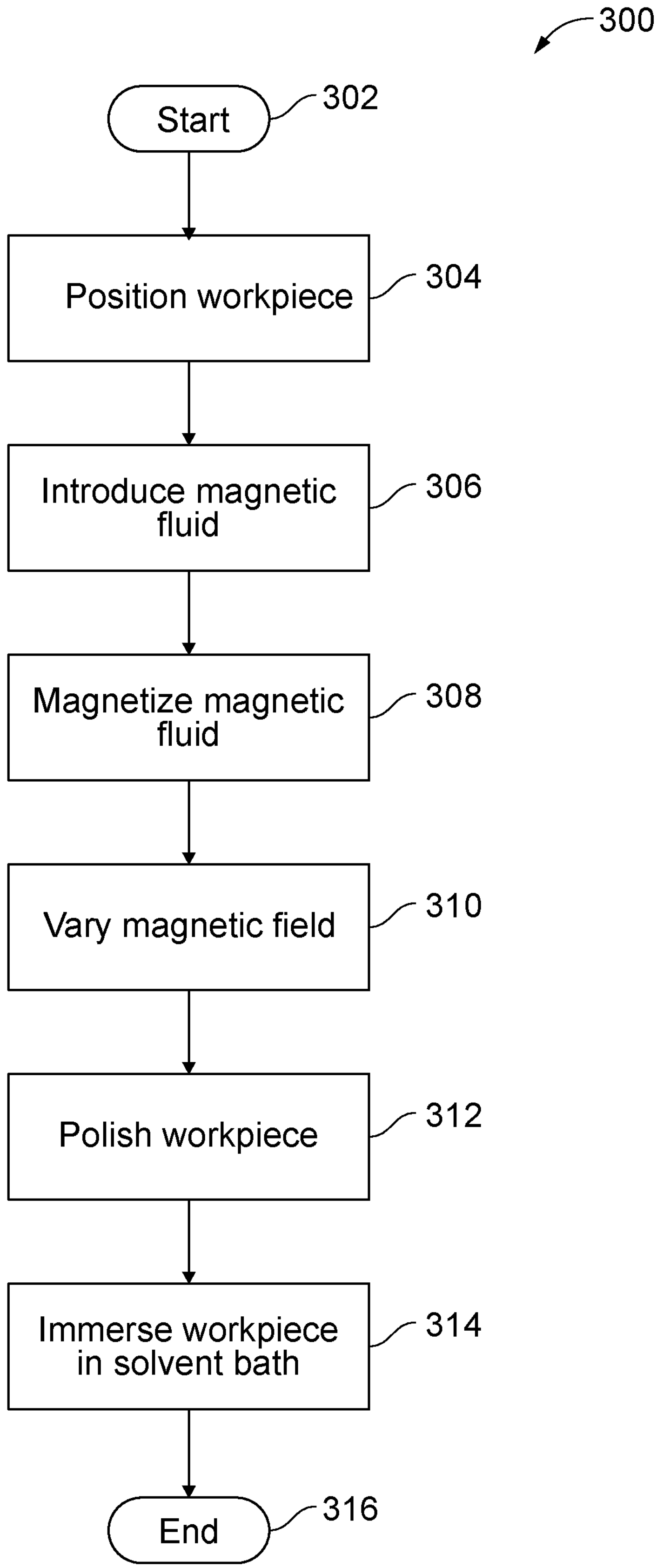
300
Start
302
Position workpiece
304
Introduce magnetic fluid
306
Magnetize magnetic fluid
308
Vary magnetic field
310
Polish workpiece
312
Immerse workpiece in solvent bath
314
End
316

FIG. 3

METHOD AND APPARATUS FOR PERFORMING TARGETED POLISHING VIA MANIPULATION OF MAGNETIC-ABRASIVE FLUID

CROSS-REFERENCE TO RELATED APPLICATIONS

This applications claims priority to, and incorporates by reference for any purpose the entire disclosure of, U.S. Provisional Patent Application No. 62/205,257, filed on Aug. 14, 2015.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH AND DEVELOPMENT

This invention was made with government support under Grant No. 1437139 awarded by the National Science Foundation. The government has certain rights in the invention.

BACKGROUND

Field of the Invention

The present application relates generally to polishing of surfaces and more particularly, but not by way of limitation, to polishing of freeform external and internal surfaces via manipulation of magnetic-abrasive fluid.

History of the Related Art

Hand held buffers and polishers are commonly utilized in applications requiring localized polishing. Use of such equipment, however, demands dexterity and is highly tedious. As an alternative approach, electrochemical and electromechanical etching methods have been investigated and utilized in the fabrication of microstructures on silicon wafers. This process requires physical barriers to confine the electrolyte into a preferred area. In many cases, locations for targeted polishing are inaccessible for conventional polishing heads and localized polishing is difficult to achieve via free-abrasive finishing methods.

As such, a need is recognized for localized finishing and surface modification technologies. For instance, in the case of bio-medical implants, certain areas are required to be rough to facilitate bone ingrowth while other areas are required to be smooth to reduce friction, wear, fatigue, damage, and corrosion. A deterministic and localized polishing method is required for polishing of desired areas without disturbing adjacent rough surfaces.

SUMMARY

The present application relates generally to polishing of surfaces and more particularly, but not by way of limitation, to polishing of freeform external and internal surfaces via manipulation of magnetic-abrasive fluid. In one aspect, the present invention relates to a magnetic field manipulated localized polishing system. The magnetic field manipulated localized polishing system includes a container holding a volume of a magnetic abrasive fluid. The magnetic abrasive fluid contains abrasive particles. A motor is positioned under the container. A magnet is coupled to the motor such that the motor induces rotation of the magnet. A workpiece is suspended in the container.

In another aspect, the present invention relates to a method for magnetic abrasive polishing. The method includes positioning a workpiece in a container. A magnetic abrasive fluid is introduced to a space under the workpiece.

The magnetic abrasive fluid is magnetized via a magnet. A resulting magnetic field is varied by rotating the magnet to apply a magnetic field gradient to the workpiece. Travel of magnetic particles present in the magnetic abrasive fluid is induced to affect localized polishing of the workpiece.

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the present invention and for further objects and advantages thereof, reference may now be had to the following description taken in conjunction with the accompanying drawings in which:

FIG. **1**A is a front view of an MFMLP system according to an exemplary embodiment;

FIG. **1**B is a schematic view of the MFMLP system of FIG. **1**A according to an exemplary embodiment;

FIG. **2**A is a diagrammatic representation of an interface between a magnetic fluid and a workpiece according to an exemplary embodiment;

FIG. **2**B is a diagrammatic illustration of a magnet acting on a magnetic fluid according to an exemplary embodiment;

FIG. **2**C is a diagrammatic illustration of a magnetic abrasive fluid acting on a workpiece according to an exemplary embodiment; and

FIG. **3** is a flow diagram illustrating an MFMLP process according to an exemplary embodiment.

DETAILED DESCRIPTION

Various embodiments of the present invention will now be described more fully with reference to the accompanying drawings. The invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein.

In general, surface polishing of a component has three requirements. First, there must be sufficient contact force between the surface to be polished and the polishing abrasive. Second, there must be relative motion between the surface to be polished and the polishing abrasive. Third, the hardness of the polishing abrasive must be sufficient to overcome the shear modulus of the surface to be polished so as to affect asperity removal. FIG. **1**A is a front view of an MFMLP system **100**. FIG. **1**B is a schematic view of the MFMLP system **100**. Referring to FIGS. **1**A-**1**B together, the MFMLP system **100** includes a container **101** that houses a magnetic fluid **102**. The MFMLP system **100** also includes a motor **104** disposed below the container **101**. The motor **104** is coupled to a magnet **106**. In a typical embodiment, the container **101** is sufficiently strong to withstand accidental collision with the magnet **106** and is transparent so as to provide a clear view of the surface being polished. In an exemplary embodiment, the container **101** is constructed from a material such as, for example, soda-lime glass, which is sold under the name PYREX® by Corning, Inc.; however, in other embodiments, other materials could be utilized according to design and application requirements.

Still referring to FIGS. **1**A-**1**B, the magnet **106**, in a typical embodiment, is a neodymium (Nd—Fe—B) magnet. As illustrated by way of example in FIGS. **1**A-**1**B, the MFMLP system **100** includes two magnets **106**; however, in other embodiments, systems utilizing principles of the invention may utilize any number of magnets. In an exemplary embodiment, the magnet **106** has a magnetic field strength at 5 mm and 10 mm from the surface of the poles of approximately 0.3 T and 0.1 T, respectively. Specifications of an exemplary magnet **106** are listed below in Table 1; however, in other embodiments, magnets of differing types and properties could be utilized according to application and design requirements.

Dimensions	20 mm diameter × 20 mm thick
Material	NdFeB
Grade	N52
Plating/Coating	Ni—Cu—Ni
Magnetization Direction	Axial (Poles aligned on flat ends)
Weight	24.1 g
Pull Force	16.6 lbs
Surface Field	0.64T
Maximum Operating Temperature	176° F.
Residual Flux Density (B_{rmax})	1.32T

Still referring to FIGS. **1A-1B**, in a typical embodiment, the motor **104** is a 3 W motor with a loaded speed of approximately 600 RPM. The magnet **106** is coupled to the motor in such a way that the magnet **106** rotates when power is applied to the motor **104**. In a typical embodiment, the magnet **106** is mounted off-center of an axis of rotation of the motor **104**. Additionally, the magnet **106** is mounted slightly offset from a vertical axis of the magnet **106**. Thus, as the magnet **106** rotates with the motor **104**, the magnet **106** traces an approximately conical-shaped pattern. The container **101** is disposed on a platform **108** above the motor **104** and the magnet **106**. The platform **108** is inclined at an angle of approximately 5 degrees from horizontal. Due to the increased distance from the container **101** to the magnet **106**, such inclination provides a curvilinear variation of a magnetic field of the magnet **106** sufficient to induce agitation of the magnetic fluid **102**.

The embodiment described in FIGS. **1A-1B** is appropriate for polishing flat or nearly flat concave and convex surfaces. In other embodiments, an array of magnets is disposed in close proximity to the container **101** containing the magnetic fluid **102**. Vibration of the magnets produces the spatial and temporal variations in the magnetic field necessary to excite the magnetic fluid **102** and achieve polishing. Such an arrangement is useful for complex surfaces requiring precise location of the polishing material.

Still referring to FIGS. **1A-1B**, the magnetic fluid **102** is an abrasive magnetic slurry suspended in a matrix of mineral oil. In a typical embodiment, approximately 20%-40% of the volume of the magnetic fluid **102** includes abrasive particles **202** (shown in FIG. **2A**). In an exemplary embodiment, the abrasive particles **202** may be, for example, silicon carbide (SiC) with an average diameter of 15 μm; however, in other embodiments, abrasives of different materials and sizes could be utilized in accordance with application requirements. In a typical embodiment, the magnetic fluid **102** includes, by way of example, ferromagnetic carbonyl iron particles and mineral oil. In other embodiments, surfactants in an amount less than or equal to approximately 5% are included in the magnetic fluid **102**. The abrasive particles **202** are suspended in the magnetic fluid **102**. In a typical embodiment, the magnetic fluid **102** is characterized as a semisolid fluid.

Still referring to FIGS. **1A-1B**, a workpiece **110** having a surface to be polished is suspended in the container **101**. A compressible barrier **112** is fitted around a perimeter of the workpiece **110**. The workpiece **110** is positioned such that the compressible barrier **112** contacts a bottom interior face of the container **101** thereby creating a sealed region under the workpiece **110** so as to prevent the magnetic fluid **102** from escaping in a lateral direction. The magnetic fluid **102** is introduced to the sealed region. In a typical embodiment, a downward force is applied to the workpiece **110** in an amount sufficient to cause sustained contact between the surface to be polished and the magnetic fluid **102**.

FIG. **2A** is a diagrammatic representation of an interface between a magnetic fluid **102** and the workpiece **110**. FIG. **2B** is a diagrammatic illustration of the **106** magnet acting on the magnetic fluid **102**. FIG. **2C** is a diagrammatic illustration of a magnetic abrasive fluid (such as the magnetic fluid **102**) acting on the workpiece **110**. Referring to FIGS. **2A-2C** collectively, during operation, the workpiece **110** is lowered into the container **101** until a gap between the bottom interior face of the container **101** and the surface to be polished is approximately 1 mm. In a typical embodiment, a downward force is applied to the workpiece **110** in an amount sufficient to cause sustained contact between the surface to be polished and the magnetic fluid **102**. The magnetic fluid **102** is introduced to the space defined by the compressible barrier **112** underneath the workpiece **110**. The magnetic fluid **102** is magnetized by the magnet **106** coupled to the motor **104**. A magnetic field of the magnet **106** is varied by rotating the motor **104** and the magnet **106** for a pre-determined polishing time ranging from, for example 10 minutes or less to 60 minutes or more. During polishing, a magnetic field of a specified varying spatio-temporal pattern is applied to the magnetic fluid **102**. As shown in FIG. **2B**, magnetic particles present in the magnetic fluid **102** will agglomerate in regions of higher magnetic field intensity. Such agglomeration, together with drag exerted by the magnetic fluid **102** itself, will cause the abrasive particles to be carried along the surface of the workpiece **110** thereby causing removal of asperities.

Still referring to FIGS. **2A-2C**, the magnetic field gradient causes application of a significant normal force to the workpiece **110**. In typical embodiments, the normal force can be the result of mechanical downforce applied to the workpiece **110** or through the pull of magnetic fluid **102** on the surface of the workpiece **110** through the applied magnetic field. Variations in the magnetic field tangent to the surface to be polished cause the magnetic fluid **102** to flow and agitate locally against the workpiece **110**. Spatio-temporal variations in the magnetic field, coupled with the flow pattern, determines the stiffness of the polisher. That is, regions of high magnetic-field intensity will expose a greater number of abrasive particles to the workpiece **110** thereby creating a stiffer polishing action. Alternatively, regions of lower magnetic-field intensity will expose fewer number of abrasive particles to the workpiece **110** thereby resulting in a softer polishing action. As shown in FIG. **2C**, during polishing, the magnetic fluid **102** is moved laterally or rotated in the vicinity of a targeted area of the workpiece **110** responsive to the desired spatio-temporal distributions of the magnetic field. Application of the magnetic field tends to cause limited separation of the abrasive particles **202** and the magnetic particles **204** present in the magnetic fluid **102**. As shown in FIG. **2A**, during polishing, the abrasive particles **202** are lifted upwardly towards the workpiece **110** as the magnetic particles **204** are pulled downwardly by the magnet **106**. In a typical embodiment, polishing is confined to locations where sufficient normal force exists. After polishing, the workpiece **110** is removed and immersed in a bath of a solvent such as, for example, heptane to dissolve stains resulting from the magnetic fluid **102**.

FIG. **3** is a flow diagram illustrating an MFMLP process **300** according to an exemplary embodiment. The process **300** begins at step **302**. At step **304**, the workpiece **110** is positioned in the container **101**. At step **306**, the magnetic fluid **102** is introduced to a space under the workpiece **110**. At step **308**, the magnetic fluid **102** is magnetized by the magnet **106**. At step **310**, a magnetic field of the magnet **106** is varied by rotating the motor **104** and the magnet **106** to apply a magnetic field gradient to the workpiece. At step **312**, the magnetic field gradient induces travel of magnetic particles present in the magnetic fluid **102** so as to affect localized polishing of the workpiece **110**. At step **314**, the workpiece **110** is removed and immersed in a bath of heptane. The process **300** ends at step **316**.

Although various embodiments of the method and system of the present invention have been illustrated in the accompanying Drawings and described in the foregoing Specification, it will be understood that the invention is not limited to the embodiments disclosed, but is capable of numerous rearrangements, modifications, and substitutions without departing from the spirit and scope of the invention as set forth herein. It is intended that the Specification and examples be considered as illustrative only.

What is claimed is:

1. A magnetic field manipulated localized polishing system comprising:

a container holding a volume of a magnetic abrasive fluid, the magnetic abrasive fluid containing abrasive particles;

a motor positioned under the container;

a magnet coupled to the motor such that the motor induces rotation of the magnet;

a workpiece suspended in the container;

a compressible barrier having a portion thereof extending downwardly perpendicular to the container, the compressible barrier being spaced apart from a side interior face of the container and positioned around and extending below the workpiece and contacting the container so as to create a sealed region under the workpiece, the magnetic abrasive fluid being contained in the sealed region; and

wherein movement of the magnet produces spatial and temporal variations in a magnetic field produced by the magnet that excites the magnetic fluid.

2. The magnetic field manipulated localized polishing system of claim **1**, wherein the abrasive particles comprise silicon carbide.

3. The magnetic field manipulated localized polishing system of claim **1**, wherein:

the container is positioned on a platform above the motor; and

the platform is inclined at an angle relative to horizontal.

4. The magnetic field manipulated localized polishing system of claim **3**, wherein inclination of the platform induces curvilinear variation of a magnetic field of the magnet sufficient to induce agitation of the magnetic abrasive fluid.

5. The magnetic field manipulated localized polishing system of claim **1**, wherein the magnet is mounted off-center of an axis of rotation of the motor.

6. The magnetic field manipulated localized polishing system of claim **5**, wherein the magnet is slightly tilted relative to vertical.

7. The magnetic field manipulated localized polishing system of claim **1**, wherein the magnetic abrasive fluid is suspended in mineral oil.

8. The magnetic field manipulated localized polishing system of claim **1**, wherein the abrasive particles have a diameter of approximately 15 μm.

9. The magnetic field manipulated localized polishing system of claim **1**, wherein the portion extends downwardly perpendicular to a bottom interior face of the container, and wherein the sealed region is formed by the compressible barrier contacting the bottom interior face of the container such that the magnetic abrasive fluid is within the sealed region.

10. A method for magnetic abrasive polishing, the method comprising:

positioning a workpiece in a container;

positioning a compressible barrier having a portion thereof extending downwardly perpendicular to the container around the workpiece, the compressible barrier contacting the container so as to create a sealed region between the workpiece and the container, wherein the compressible barrier is spaced apart from a side interior face of the container and extends below the workpiece;

introducing a magnetic abrasive fluid to a space under the workpiece within the sealed region;

magnetizing the magnetic abrasive fluid via a magnet;

varying a resulting magnetic field by rotating the magnet to apply a magnetic field gradient to the workpiece; and

inducing travel of magnetic particles present in the magnetic abrasive fluid, via spatial and temporal variations in the magnetic field, to affect localized polishing of the workpiece.

11. The method of claim **10**, comprising removing the workpiece and immersing the workpiece in a bath of a solvent.

12. The method of claim **10**, comprising adjusting, via the spatial and the temporal variations in the magnetic field, a stiffness of a polishing action achieved by the magnetic abrasive fluid.

13. The method of claim **12**, wherein the magnet is tilted relative to vertical.

14. The method of claim **10**, comprising applying a downward force to the workpiece sufficient to cause sustained contact between the workpiece and the magnetic abrasive fluid.

15. The method of claim **10**, wherein the magnetic abrasive fluid is moved responsive to variations in the resulting magnetic field.

16. The method of claim **10**, wherein a stiffness of a polishing action is varied with the resulting magnetic field.

17. The method of claim **16**, wherein the varying the resulting magnetic field causes fewer abrasive particles to be exposed to the workpiece in regions of low magnetic field intensity and a greater number of abrasive particles being exposed to the workpiece in regions of high magnetic field intensity.

18. The method of claim **10**, wherein the portion extends downwardly perpendicular to a bottom interior face of the container, and wherein the sealed region is formed by the compressible barrier contacting the bottom interior face of the container such that the magnetic abrasive fluid is within the sealed region.

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